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LOW-LEVEL FLIGHT SIMULATION:
VERTICAL CUES

By

Elizabeth L. Martin
Edward J. Rinalducci

OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85224

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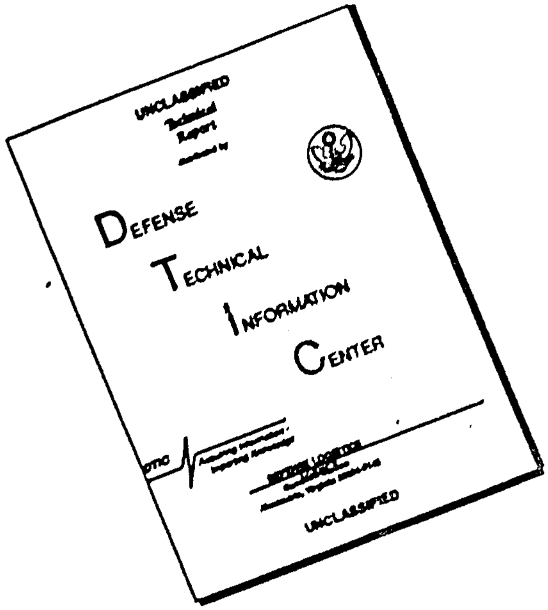

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report presents the results of two studies investigating the impact of variations in vertical cue characteristics on pilot performance on a simulated low-level flight task. The studies were conducted in the Advanced Simulator for Pilot Training in its F-16 configuration. Subjects were pilots transitioning to the F-16 aircraft. The experimental task consisted of flying a course that had irregularly placed vertical cues. The pilots' task was to maintain an assigned altitude and airspeed. The pilots' ability to maintain the specified altitude was analyzed for level flight and turning flight. The frequency of terrain crashes was also monitored.

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Study I compared the effect on performance of two cue densities (1500-feet or 4500-feet) and two cue shades (white or black). The cues were tetrahedrons 75 feet in height. Study II compared the effects on performance of two airspeeds (300 knots or 540 knots) and three cue configurations (inverted all black tetrahedrons, inverted tetrahedrons with black bottoms and white tops, white triangles placed directly on the ground). The cues were inverted tetrahedrons 35 feet in height. The results of Study I demonstrated that altitude control was better using white cues and the more dense cue condition. Terrain avoidance was aided by increased density but not affected by cue shade.

Study II demonstrated that (a) altitude control was better at a slower airspeed, (b) inexperienced (but not experienced) pilots did better with the vertically developed cues than with the flat cues, and (c) the vast majority of terrain crashes occurred in the white triangle only condition for both experienced and inexperienced pilots. Recommendations included maximizing cue contrast and using a vertical cue density level of at least 1500 feet.

SUMMARY

Objectives

The objectives were to assess the relative impacts of cue density, cue shade, linear perspective cueing, airspeed, and pilot experience on performance of a low-level flight task in a computer-generated image (CGI) simulation environment.

Background/Rationale

Frequently, CGI scenes have been criticized for not providing sufficient close-to-the-ground scene detail to support training in the low-altitude flight domain. Recent research and development (R&D) has indicated that abstract and simple cues have the potential of enhancing low-level flight performance in simulated visual environments. However, the minimum acceptable detail for various aspects of low-level flight scenes has not been determined. The present R&D was designed to obtain information on this issue–information for use in specifying minimum design goals for future visual system procurements and guidelines for data-base modeling on current systems.

Approach

The studies were conducted in the Advanced Simulator for Pilot Training in its F-16 configuration, using both experienced and inexperienced fighter pilots transitioning into the F-16 aircraft. Each pilot flew through a simulated low-level course at a specified altitude and airspeed. The ability to maintain the assigned altitudes under differing visual scene test conditions was used to assess the usefulness of the various visual cues fused for low-level flight.

Specifics

Method. Experiment I compared the effects of different terrain cues on the ability of eight pilots with no operational fighter experience to maintain 100 feet above ground level (AGL) at 450-knots airspeed on a low-altitude course. The terrain cues were vertical tetrahedrons 75 feet high at two densities (separations of 1500 or 4500 feet) and two cue shades (black or white).

Experiment II compared the effects of three terrain-cue configurations and two airspeeds (300 or 540 knots) on the ability of two groups of pilots (5 experienced and 13 inexperienced fighter pilots) to maintain 200 feet AGL throughout the same course used in Experiment I. The terrain cue configurations were (a) all-black inverted 35-foot high tetrahedrons, (b) inverted tetrahedrons of the same type with black bottoms and white tops, and (c) "flat" white triangles place directly on the ground, all at a single density (separations of approximately 1500 feet apart).

Findings and Discussion. In Experiment I, altitude control was better using the white-cue (32-foot difference in mean altitude) and the denser-cue conditions (13-foot difference in mean altitude). Terrain cues were more effective in level flight than in maneuvering flight. Terrain avoidance was aided by increased density but not affected by cue shade.

In Experiment II, altitude control was superior for the slower 300 knots airspeed (91-foot difference in mean altitude). The inexperienced pilots did better (45-foot difference in mean altitude) with the white-topped cones than with the flat white triangles. For both types of pilots, the vast majority of terrain crashes occurred in the white-triangle-only condition, i.e., with no vertically developed terrain cues.

Conclusions/Recommendations

1. Variations in the density, height, and shade of simple terrain cues can affect the quality of low-level flight performance in a simulated visual environment.

2. A density averaging 1500 feet between terrain-cues should be used to aid simulated low-level flight, especially with higher airspeeds and less-experienced pilots.

3. Terrain-cue heights of as little as 35-foot height are preferable to "flat" cues–i.e., to cues of zero height placed directly on the ground.

4. The target-to-background contrast of the cues should be maximized, especially with low display luminance levels.

5. The role of scene content around the horizon during maneuvering flight should be investigated since vertically developed terrain cues are relatively effective during this phase of low-level flight.

PREFACE

This research represents a portion of the research program of the Air Force Human Resources Laboratory (AFHRL) Technical Planning Objective 3, the thrust of which is Air Combat Tactics and Training. The general objective of this thrust is to identify and demonstrate cost-effective training strategies and training equipment capabilities for use in developing and maintaining the combat effectiveness of the Air Force aircrew members. More specifically, the research was part of the research program conducted under the Air Combat Training Research subthrust, which has as its goal to provide a technology base for training high level and quickly perishable skills in simulated combat environments. Work Unit 11230332, Terrian Visual Cue Requirements for Flight Simulation, addressed a portion of this subthrust: the effects of vertical cues of performance in a simulated low-level flight environment. Mr. James F. Smith was the project scientist, Mr. Robert Woodruff was the task scientist, and Dr. Elizabeth L. Martin was the principal investigator.

Dr. Edward J. Rinalducci conducted Study II while at the Operations Training Division of AFHRL on the Summer Faculty program of the Southeastern Conference of Electrical and Electronics Engineers sponsored by the Air Force Office of Scientific Research.

The authors would like to express their appreciation to many colleagues whose assistance was invaluable; specifically thanks go to Ms. Sherri Patterson and Mr. Steven Stephens for their visual modeling efforts, to Ms. Pam Kosirog for her performance measurement programming, to Mr. Mike Hardy and Mr. Tien Fu Sun for their assistance in data reduction and analysis, to Mr. Tom Farnan for his patience and expertise in console operation, to Ms. Harriet Webb and Ms. Kathy Sherman for their assistance in preparing the manuscript, and to Mr. Gavin Lidderdale and Mr. James Smith for their continuing interest, guidance, and editiorial comments. Special thanks go to the many Air Force pilots who participated in this research.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

List of Tables (*Continued*)

LOW-LEVEL FLIGHT SIMULATION: VERTICAL CUES

I. INTRODUCTION

Low-level flight has become one of the most important fighter aircraft tactics. Pilots' proficiency in low-level tactical flight is of paramount importance to mission effectiveness. In support of a ground attack mission, the pilot is expected to fly at high speeds over unfamiliar, heavily defended terrain at 100 feet or less. Unfortantely, today's peacetime flight environment is not well suited for training that type of flight. Restrictions on where, how often, and how low severely limit the opportunities for the pilot to acquire the degree of proficiency that combat readiness demands.

The potential advantages of using a simulated environment for this type of training range from safety for the transitioning pilot to more realistic combat scenario training for the mission ready pilot. However, the opportunity for flight simulation to provide a supplementary learning environment for tactical low-level flight has been limited by inadequacies in the visual displays. Existing visual displays do not provide cues sufficient for terrain avoidance, much less for low-level tactical flight. This situation is the result of two deficiencies: (a) lack of basic understanding of visual perceptual mechanisms required for low-level flight (real or simulated) and (b) lack of adequate display technology.

Most current and proposed visual systems are primarily of the computer-generated imagery (CGI) types, with limitations that include low resolution and luminance levels, infinity optics, low level-of-scene detail, and less than full field of view. The relative importance of these factors individually and interactively is not known. Therefore, even if visual display technology were more advanced, it would be difficult to specify the required capabilities. Recognition of these problems has resulted in a significant increase in research and development in both the engineering and behavioral areas. However, even with focus and funding priority, new off-the-shelf systems with significantly better performance will not be available until the late 1980s. Given the immediate need for an improved low-level training capability, a reasonable interim research approach is to explore alternative ways of using the existing visual systems to provide the training required.

Considering the limiting characteristics of existing visual systems, very little can be done to modify or improve items such as field of view, resolution, brightness, or infinity optics. The amount of displayable detail, usually expressed in the number of edges or point lights, is also fixed. However, accepting these limitations as given, there is still considerable latitude for alternative scene designs and definition. The major problem is that the maximum allowable detail is typically orders of magnitude less than that required for a real-world facsimile. (For comparison purposes, a commercial television scene may range from 30,000 to 500,000 edge equivalents, with an average around 100,000, whereas a typical CGI simulation scene can display 2,000 to 5,000.) Since real-world depiction has been the primary driver of scene design rather than a perceptual cue and training task analysis, it seems likely that the training potential of existing systems can be enhanced when more attention is given to cues in relation to their perceptual function.

Pilots report that plain CGI surfaces do not provide depth cues, thus making precise altitude control impossible and terrain avoidance difficult. In addition to the primary cue of retinal disparity, there are the secondary cues of aerial perspective, linear perspective, retinal image, and familiar size, texture gradient, motion parallax, streaming, interposition, height of an object in the visual field, light, and shadows, as well as the physiological cues of accommodation and convergence (Graham, 1965; Harker & Jones, 1980). The perceived flatness of many scenes may also be the result of visible monitor frames and raster patterns, as well as binocular viewing without retinal disparity. No existing visual displays provide retinal disparate images; most are collimated (precluding accommodation changes) and few are in color (precluding aerial perspective cues). The remaining cues are possible to display but vary in the amount of detail and computation required.

Since the amount of detail available is extremely limited, it should be treated as a valuable resource. The objective is to get the most function (in a perceptual sense) with the least cost (in terms of detail expended). For example, ground texture has been cited as a very important feature for the maintenance of low-level flight (Harker & Jones, 1980; Stenger, Zimmerlin, Thomas, & F[illegible]unstein, 198[illegible] however, it is prohibitively costly (in a detail allocation sense) to depict via software in most systems [illegible]his r[illegible]n, next generation systems are being designed to display ground texture using automatic hardware features [illegible] do not compete with the detail resources.

The relative importance of texture as a perceptual/performance cue has not been studied systemtically in dymanic simulation. Current thinking is that texture per se provides surface definition and that texture gradients provide velocity gradient information. Consistent with these notions are reports from CGI users that pilot acceptance of CGI scenes is increased when any detail is added to the surface. There is ample anecdotal evidence from the field and from manufacturers that any added detail aids the pilot. Kraft (1969) experimentally demonstrated that a runway environment with a lot of detail (depicting a city) resulted in better pilot performance than did a runway environment barren in details (located in a dry lake bed).

A problem has been created by a lack of dimension or metric for quantitatively comparing the amount or type of detail present in a scene. For example, along what dimensions is the runway environment of a city compared with that of a desert? A metric that might be acceptable to the engineering community, say in edges (or edge equivalents) per square mile, might be unacceptable to the psychologist since it connotes nothing about scene content. Additionally, the same object (e.g., a tree) may be modeled with six, six-hundred, or six-thousand edges. The concept of optical density may yet turn out to be useful, but it is still not clear that the semantics and the syntax of a visual scene can be assimilated into a single dimension. The question then becomes: What is the most efficient and effective type of detail to add to the surface? Generally speaking, detail can be added to the surface as angular development, as coplanar to the surface, or as a combination of these two. With respect to detail allocation and perceptual theories, each type has its advantages and disadvantages. The purpose of the present research is to investigate the requirements for vetical cues to support low-level flight within the simulator.

II. BACKGROUND

There is a general belief in the simulator community that the addition of surface texture will solve many of the problems associated with simulated low-level flight. The term "texture" is not very precise, and its recent popularity as the long-awaited panacea has not helped its status as a term with a precise meaning. Since the notion of texture involves vertical and coplanar detail (which becomes more resolvable as one approaches the surface), the following discussion classifies cues as either vertical or coplanar in nature, deferring the issue of their textural status.

Buckland, Monroe, and Mehrer (1980) experimentally investigated the role of various coplanar runway cues on approach and landing performance of experienced pilots in a simulator. There were six daytime scenes of runways (in addition to a night scene); each scene was the same size and had no other detail in the vicinity of the runway. One runway contained only centerline hash and sideline marking. The next added a runway identification number with standard markings. The next four added checkered patterns of 4-, 8-, 16-, and 25-foot squares. Each runway was tested with and without a standard 1,000-foot overrun containing chervon markings.

Although many measures of pilot performance were analyzed, the most revealing measure was vertical velocity at touchdown, commonly used as the most sensititive measure for the terminal phase of touchdown portion of the landings. The results indicated that, in the absence of an overrun, there was a significant linear decrease in touchdown vertical velocity as a function of increasing detail levels. By the addition of the overrun, the linear effect of check size was disrupted such that the 4-foot checkered pattern was still the best, but results for the others did not differ significantly. Evidently, the positive effects of edge-consuming checkered patterns were not robust. Although the disrupting effects of the chervon-marked overrun are an interesting finding, it was not pursued further.

One of the theoretical benefits of checkered patterns is the linear perspective cue. This cue should enhance perception of surface orientation. Although redundant with overall runway shape transformation in the landing situation, some form of orientation information needs to be provided when the earth's surface is intended to be anything other than flat, as in an environment of rolling hills. Non-flat terrain representation is an essential requirement for an effective simulation of a low-level flight environment. For these reasons, Buckland, Edwards, and Stephens (1981) extended the use of checkered patterns for depicting a narrow band of rolling terrain. As part of the study, the size of the check was varied from 220-, 440-, and 800-foot squares. The presence or absence of vertical cues and aircraft shadow was also manipulated. The course was 10 miles long and was made up of eight valleys (flat) separated by low rolling hills that were either 100 feet or 300 feet high. The stud was conducted in a simulated A-10 aircraft using experienced A-10 pilots who were instructed to fly nap-of-the-earth flight at 50 feet about the ground at 300 knots. The results indicated that both the vertical objects and checkered patterns significantly influenced performance. No significant effects were attributable to the aircraft shadow. Subjective pilot opinion indicated a preference for the 220-foot pattern and the presence of vertical objects. Although Buckland et al. (1981) concluded that the checkered patterns were more influential than were the vertical objects, the visual scenes did not allow for a meaningful comparison because the vertical objects were not systemmatically spaced and the size/shape dimension was not controlled.

Even the most edge-conserving vertical object (a tetrahedron requiring six edges) would have no edge utility improvement over a checkered pattern if the vertical objects required the spacing as the intersections on the checkered patterns. However, the possibility that vertical objects might be effective altitude cues with considerably large inter-cue distances was suggested after informal testing of their effects in eliminating unwanted terrain crashes in a simulated combat environment. Kellogg, Prather, and Castore (1981) reported a high incidence of terrain collisions in the conduct of a study of a simulated close air support scenario. When confronted with enemy ground threats, pilots attempted low altitude, defensive maneuvering and egress only to run into the ground inadvertently. The existing visual data base was too close to display capacity to allow for the addition of checkered patterns. Therefore, tetrahedrons were added to the visual scene in the regions associated with the largest number of terrain crashes found in the Kellogg et al. (1981) study. The objects were regularly spaced at 1,000 foot intervals. They were modeled to be 35 feet in height with shaded black bottoms and white tops. The white top was designed to provied a linear perspective cue. No formal testing of cue spacing, shape, height, or shade was conducted. However, reports from pilots who flew through the environment were favorable, and crash rates seemed to decline.

In an attempt to define systematically the effects of these vetical objects on low-level flight, Engel (1980) conducted a study on the Advanced Simulator Pilot Training/A-10 Cockpit Configuration in which the spacing of these cues was varied at 250-foot increments between 500 and 1,500 feet. There was also a condition that did not contain any of these cues. The cues were arranged in a triangular course consisting of two steep left turns (approximately a 4g turn) and three straight-and-level legs. The pilots were instructed to fly as low as they could safetly fly at 300 knots. The results indicated that the presence of the cues had a significant effect on level flight altitude compared to the no-cue density conditions. There was, however, a significant effect of the density conditions on the frequency of terrain crashes such that the more dense cue conditions were associated with fewer crashes. Several problems in the experimental design and conduct may have resulted in lack of sensitivity to cue density.

In a subsequent series of studies using a different experimental paradigm, Martin (1983) investigated the role of cue density, assigned altitude of flight, airspeed, and pilot experience in a simulated low-level flight task. Considering that body of data, the results of those studies indicate cue density has a significant effect on the ability to maintain a given altitude in level flight and on reducing the frequency of terrain crashes for both experienced and inexperienced fighter pilots. The effect of cue density was found at 540 knots of airspeed but not at 300 knots (the speed used in the Engle study). The cues used in those studies were pyramid-shaped tetrahedrons shaded black, 75 feet high; these were considerably larger than the cone-shaped cues.

The purpose of the present studies was to investigate the roles of the linear perspective cue provided by the white tops, airspeed, cue shade and density, altitude of flight, and pilot experience.

III. STUDY I: OBJECT DENSITY AND SHADE

Objectives

The results of earlier studies on vertical cueing (Martin, 1983) demonstrate the inadequacy of even the highest density cue conditions to support low-level flight during turns. The pilots often commented that the cues were not as visible from higher altitudes (e.g., 700 feet above ground level (AGL), as they would have preferred. (The ASPT visual system software automatically drops them from the scene at altitudes above 2000 feet AGL.) In an attempt to make the cues (pyramid-oriented tetrahedrons 75 feet high) more visible, the shade was changed from black to white. The results of data and comments collected informally suggested the white cues were more visible, especially at the lowest density level (average inter-cue distance of 4,500 feet). The purpose of the present study is to conduct a direct comparision between the white and black cues in a high versus low cue density environment.

Method

Subjects. Eight B course pilots participated in this study. None had previous experience as a fighter pilot; one had a previous assignment as an Air Training Command instructor pilot, and one had previously been a navigator in an F-4E aircraft. Their mean total flight time was 418 hours (range 200 to 1560), and the mean age was 24.5 (range 23 to 27).

Equipment. The ASPT was used in the conduct of Study I and Study II. This device is a research simulator originally designed with a full-mission T-37 capability. A detailed description of the original device may be found in Gum, Albery, and Basinger (1975). One cockpit has been modified to an A-10 aircraft configuration; the other cockpit has been configured as an F-16 aircraft. Both systems were designed to have the necessary cockpit and aerodynamic capabilities to support transition flight tasks such as takeoffs, approaches, and landings; instrument flight; basic navigation tasks; and conventional air-to-ground weapons (bomb and gun) delivery. Neither of the modified configurations has full-mission capabilities. The F-16 configuration was the one used in this research. The F-16 cockpit layout was designed to duplicate Block I aircraft in most major respects with the exception of the seat, which was a modified T-37 seat tilted back 27°. The following is a description of the ASPT/F-16 as it was configured for this effort.

1. *Visual.* The visual display consists of a monochromatic computer-generated image displayed through seven cathode-ray tubes (CRTs) with a ± 150° horizontal (H) by + 110° vertical (V) field of view. The ASPT has a − 15° view over the nose, − 37° over the left side, and − 15° over the right side. (The aircraft field of view is 360° H by + 180°, − 40° over the side, and − 15° over the nose.) The resolution of the display is approximately 6 arc numbers.

2. *Kinesthetic.* The ASPT/F-16 does not have the capability to use the platform motion system that was available in the original T-37 configuration. There is a G-seat and G-suit capability; however, no G-cueing was used in this study.

3. *Instrumentation.* All flight and engine instruments were operable with the exception of the fuel flow gauge. The horizontal situation indicator was operable, but not the inertial navigation system. Static mockups were used for the communications, chaff/flare, and electronic countermeasure panels. The heads-up display (HUD) was a operational model driven by a simulation of the flgiht control computer.

4. *Basic Flight.* Aircraft aerodynamics were modeled from sea level to 40,000 feet from 0 to 0.9 mach, and a maximum of 30° angle of attack. The simulation will continue to allow higher and faster flight but without proper atmospheric modeling and drag coefficients. Engine performance was modeled from idle to afterburner and from sea level to 55,000 feet. The aerodynamic model did not account for weapon drag or station numbers, but did account for weapon weight.

5. *Weapons Systems.* The configuration included air-to-ground simulation of manual bomb and strafe modes, continuously computed impact point also with bombs and strafe, and dive toss deliveries. The potential ordinance included BDU 33, CBU 68, MK 61, MK 82 (high and low drag), and MK 106. For the delivery modes and listed ordnance, the stores management system displayed proper indications. The simulation did not include air-to-ground missile deliveries nor air-to-air capabilities.

6. *Instructional Features.* In addition to the aircraft simulation, the ASPT/F-16 provided several instructional features that were used in this study. A video display of the HUD (Figures 1 and 2) and forward out-of-the-cockpit visual scene was projected on a CRT monitor on the instructor console. A graphic display of the aircraft position was also available at the console. Either of these displays could be videotaped with associated voice communications. The current status of any relevant aircraft system states was displayed on an alphanumeric CRT. Automated objective peformance measurement was available via the student data system (see Fuller, Waag, & Martin, 1980, for a description) and a data record system that allows for the recording of up to 20 variables at 30 Hz. The student data system was used in this effort.

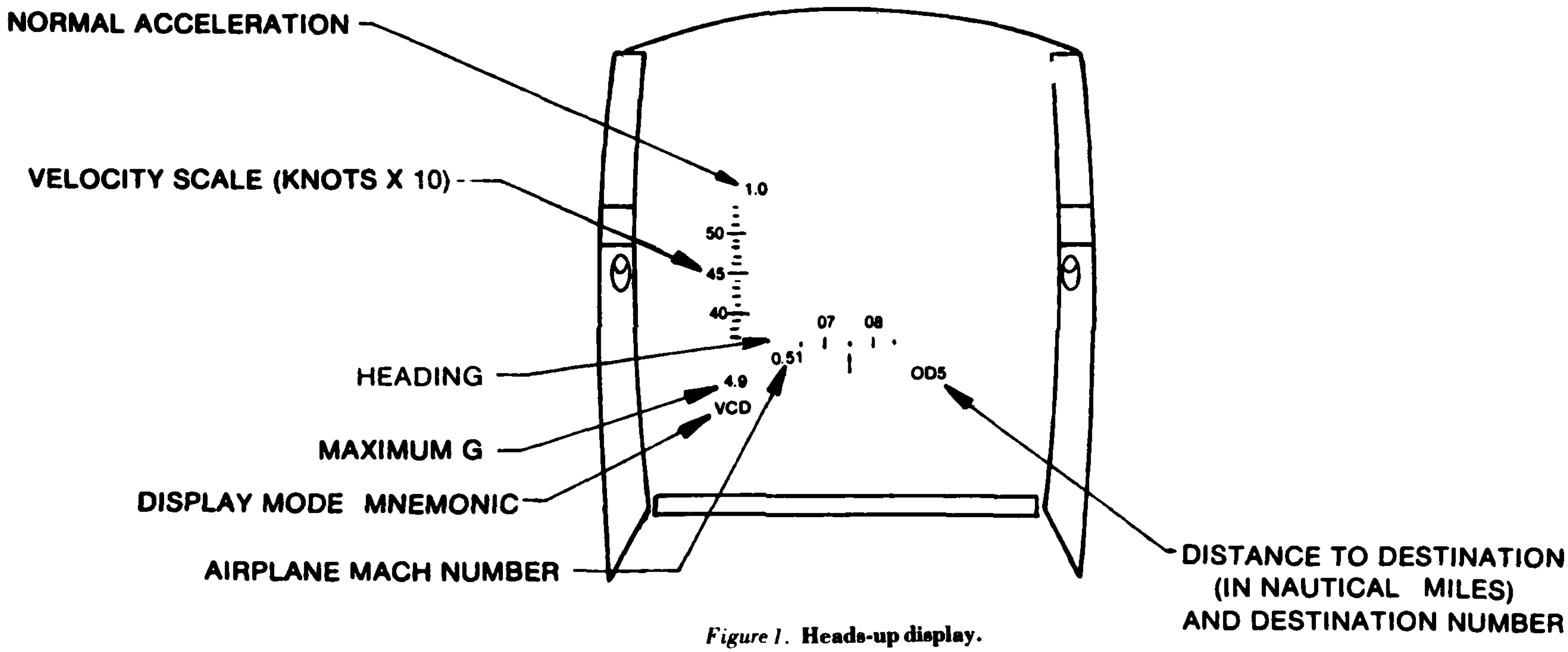

Figure 1. **Heads-up display.**

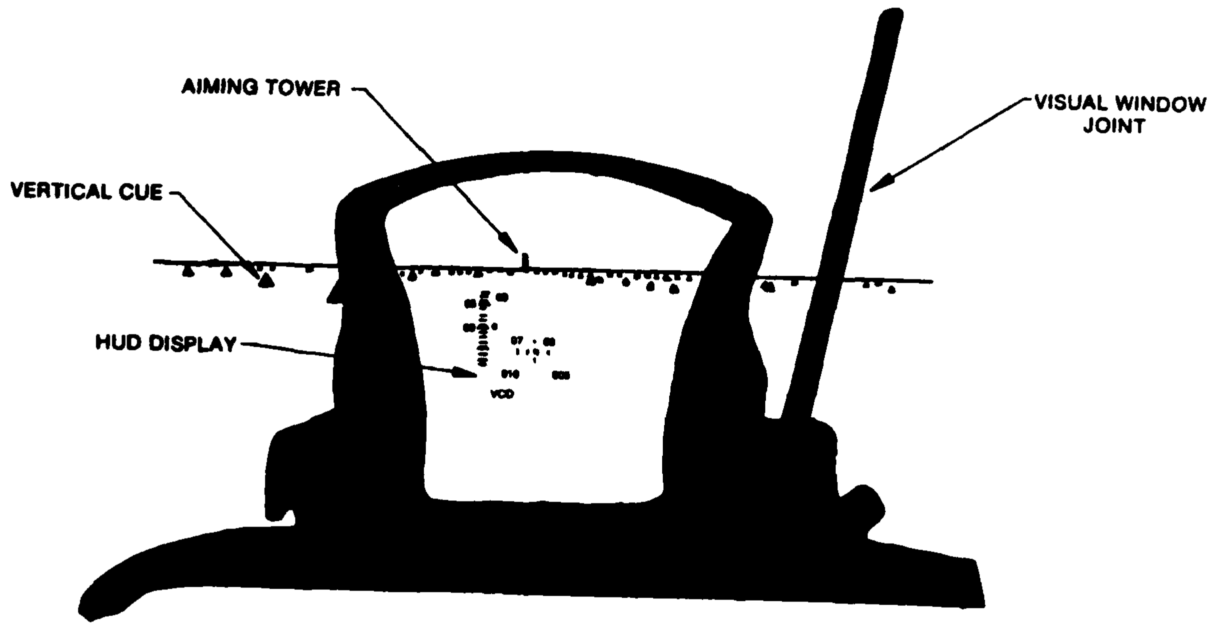

Figure 2. **Pilots view.**

7. *Task Description.* The experimental task consisted of a three-legged course containing one left turn after the first leg and one right turn after the second leg. Each leg was 8 nautical miles (nm) long and 2 nm wide. Each turn was a right angle turn requiring a 90° heading change (see Figure 3). The vertical cues were contained within the course boundaries and were distributed in such a way that the mean inter-cue distance met the experimental test requirements– either 1,500, 3,000, or 4,500 feet. The selection of cue density and shade could be accomplished manually by the experimenter from the simulator operator console or by preprogrammed software control.

The pilot's task was to fly through the course at the assigned altitude. An aiming tower 450 feet high was located at the end of each leg. A tone was delivered through the pilot's headset as a cue to initiate each turn. The delivery of the tone was controlled by preprogrammed software which monitored the aircraft's position along the course. At 540 knots, the course could be navigated if the pilot executed a 5g to 6g turn when the tone sounded. (Preliminary testing had found that navigation through the course at low altitudes was extremely difficult without addition of some navigational aids. The aiming towers and tone were included for these reasons.)

The shade of the aiming tower matched the shade of the cue on each trial. In order to control the optical flow rate as determined by the aircraft's airspeed, the pilot was given a verbal cue in his headset by a computer-generated voice. Whenever the airspeed exceeded or fell below the desired airspeed by more than 30 knots, the voice would say "high, high," etc. or "low, low," etc. until the ±30-knots tolerance was reattained. (The vocabulary of the computer voice did not include "fast" or "slow." Unfortunately, the words "high" and "low" more naturally connote altitude rather than airspeed. However, emphasis during instructions and one experience during the practice trial seemed to eliminate confusion.) Each trail was initialized at the same point. Each trial was automatically terminated when the aircraft position was laterally adjacent to the final aiming tower. A terrain crash was determined to have occured when the aircraft's center of gravity reached 0 feet AGL.

In the event of a terrain crash, the trail was automatically terminated, and the aircraft was repositioned at the starting point. When the aircraft crashed, the visual display changed to white (using preprogrammed insertion of the "temporary cloud" feature avaliable on the ASPT.) The vertical cues had no reality status, thus allowing the aircraft to pass through them without crash indications. In order to ensure that the pilots were using the external vertical cues to guide their flight altitude, the cockpit altimeter was covered and disabled. A specially programmed HUD display was used which provided heading, airspeed, g force, and distance measuring equipment, information (i.e., no flight path, pitch, altitude, nor bank information).

8. *Experimental Design and Procedures.* A 2x2 factorial, repeated-measures experimental design was used in this study. Two levels of cue shade (white and black) and two levels of cue density (1,500 and 4,500 feet) were manipulated. Each subject was exposed to each experimental condition twice. The sequence of condition presentations was counterbalanced. Thus, each subject was run on eight test trails. The test trails were preceded by two practice trails. All practice trails used a cue density that was intermediate to the two test conditions (i.e., the mean inter-cue distance was 3,000 feet. The cue shade was alternated between trails, and the between-subject sequence of cue shade was counterbalanced.

1. *Independent Variables.* The two independent variables in this study were cue shade (black and white) and cue denisty (1,500 and 4,500 feet). The cues were tetrahedrons 75 feet high with a 32-foot base. The luminance levels were as follows (as measured by a Pritchard photometer): (a) black cue 2.2 foot-lambert, (b) white cue 1.3 foot-lambert, (c) gray ground .61 foot-lambert and (d) the sky 1.0 foot-lambert. These values represent the luminance as measured from the front CRT. The levels varied somewhat across the various channels and within locations on the channels.

2. *Control Variables.* Airspeed (540 knots and task altitude (100 feet AGL) were held constant across conditions. The 540-knot airspeed was selected because it is a representative F-16 fighter/attack low-level airspeed and because previous research had shown that performance was sensitive to cue density at this airspeed but not at 300 knots. A task altitude of 100 feet AGL was chosen because previous research demonstrated sensitivity to independent variables with less within- and between-subject variability in height control. Pilots also subjectively reported that 100 feet was easier to discriminate than 50 feet or 150 feet.

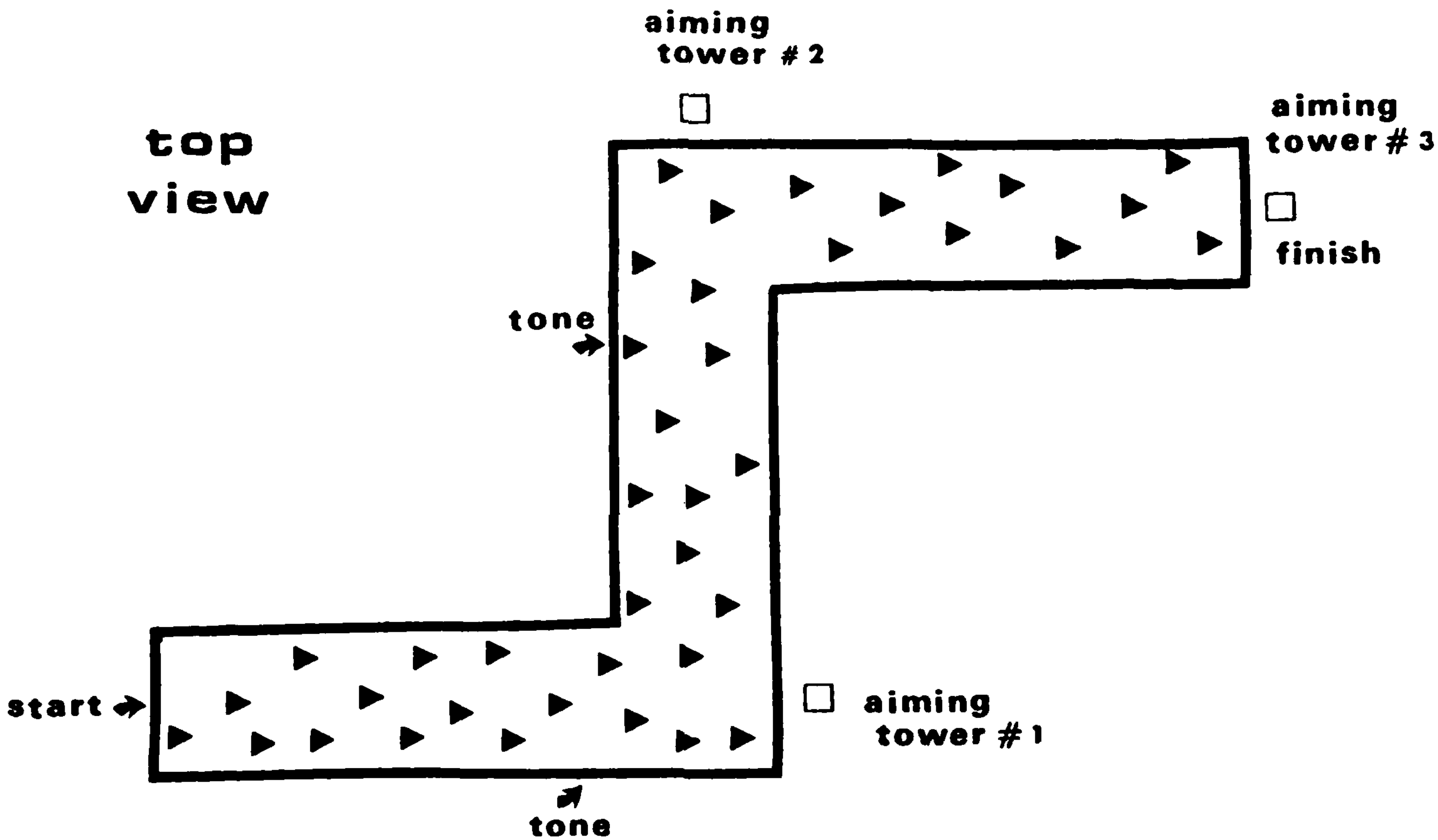

Figure 3. **Three-legged course.**

3. *Dependent Measures and Data Analyses.* Six dependent measures of pilot performance were analyzed: (a) Root Mean Square (RMS) altitude for the entire course, (b) RMS altitude for level flight, (c) RMS altitude for the turns, (d) mean altitude for the entire course, (e) mean altitude for level flight, and (f) mean altitude for the turns. A turn was defined as a bank angle greater than 30°. Level flight was defined as bank angle equal to or less than 30°. The automated performance measurement logic separated each leg and each turn as well as providing overall course measurement. In the event of a terrain crash, the x, y coordinates, airspeed, g-force bank, and pitch position at impact were recorded. These six variables were analyzed using a multivariate analysis of variance (MANOVA), followed by univariate $\underline{F}$ tests. The proportion of variance accounted for by each of the variables found to be statistically significant ($\underline{p} < .05$) on the $\underline{F}$ tests was computed the omega-squared statistic.

Results

The issue of interest in this study was the influence of vertical cue density and shade on the pilot's ability to maintain flight at 100 feet AGL. For inclusion of a measure of control, RMS, as well as altitude, was analyzed for level flight, turning flight, and entire course (level and turning flight combined). Additionally, measure of strength of association, omega squared, was included to provide an index of the relative amount of variance accounted for by the statistically significant factors.

Tables 1 and 2 present the mean and RMS data, and Tables 3 to 5 present the source tables for the MANOVA and univariate $\underline{F}$ tests with associated omega-squared values.

Table 6 depicts the distribution of terrain crashes. In the event of a terrain crash, only the data collected to the point of the crash were included for analysis; i.e., no attempt was made to estimate values for the remainder of the trial. Since most crashes occurred coming out of the second turn or near the beginning of the third leg, the lost data were primarily from the third leg.

As shown in Tables 1 and 2, flight levels were consistently between 100 and 200 feet AGL. Level flight values were relatively close to the assigned 100-foot altitude with flight paths rising 50 to 75 feet in the turns. With respect to the independent variables, the flight heights are generally lower for the 1500-foot density condition than for the 4500-foot condition and lower for the white cues than for the black.

Statistical analysis of the mean data revealed that there were reliable main effects for both cue density and cue shade when considering the entire course performance. These effects are also reliable when considering only level flight, but the main effect of cue density was not found to be reliable for maneuvering flight. Evidently, cue density provides a significant cue in level flight but is not a significant factor (at the two levels tested) in aiding altitude control during the turns. The influence of the white cue shade was consistent for both level and turning flight, regardless of cue density (i.e., a main effect with no interaction with density).

Examination of Table 2 reveals a similar but somewhat different pattern of results. The differences associated with cue density but not cue shade are significant for level flight. The opposite is true for turning flight; i.e., cue shade but not density is a significant performance factor.

The pattern of results from the statistical analyses reveals that both cue density and cue shade reliably affect pilot performance on this task such that performance is better with more cues, and white cues are better than black ones. Cue density contributes most of its influence during level flight, whereas shading influences turning flight. In addition to the statistically significant effects, the magnitude of these effects are of interest in determining the pragmatic consequences of the differences. During level flight, the average difference in altitude was about 13 feet between the 1500-foot cue spacing and the 4500-foot cue spacing. The difference associated with cue shade was only about 9 feet in average level flight altitude. A statistical index of magnitude of effect (w^2) indicates that 15% of the variability can be accounted for by the difference in cue density and about 4% by cue shade. In turning flight, about 9% of the variance is accounted for by cue shade. The real-world impact of these types of differences is included in the Discussion section.

Table 1. **Mean Altitude**

Cue Shade	Cue Density: 1500 Feet	Cue Density: 4500 Feet	$\bar{X}$
	Total Course		
White	121.76	132.14	126.95
Black	135.57	143.77	139.67
$\bar{X}$	128.66	137.95	
	Level Flight		
White	107.03	121.73	114.38
Black	115.31	127.15	121.23
$\bar{X}$	111.17	124.44	
	Turning Flight		
White	175.18	164.26	169.72
Black	201.59	210.23	205.92
$\bar{X}$	188.39	187.25	

Table 2. **Mean RMS Altitude**

Cue Shade	Cue Density: 1500 Feet	Cue Density: 4500 Feet	$\bar{X}$
	Total Course		
White	134.99	145.78	140.38
Black	152.48	157.99	155.23
$\bar{X}$	143.73	151.88	
	Level Flight		
White	112.55	131.52	122.03
Black	123.09	133.22	128.16
$\bar{X}$	117.82	132.37	
	Turning Flight		
White	188.91	177.53	183.22
Black	223.76	222.76	223.24
$\bar{X}$	206.34	200.15	

Table 3. **MANOVA Source Table**

Component	df	Lambda	df1	df2	FO	p
Cue Density	1	.0028	6.00	2.000	117.729	.0084*
Cue Shade	1	.0074	6.00	2.00	3.974	.2147
Subject	7	.0000	42.00	12.83	7.44	.0002*
Density X Shade	1	.3543	6.00	2.00	.608	.7308
Density X Subject	7	.0000	42.00	12.83	3.19	.0139*
Shade X Subject	7	.0000	42.00	12.83	2.73	.0274*

*$p < .05$.

Table 4. **RMS Altitude Univarate Source Table Plus Omega Squared**

Source	df	F	p	w^2
		Total Course		
Density	1	3.3904	.1081	
Shade	1	11.2596	.0122*	.05
Subject	7	18.5802	.0005*	.65
Density X Shade	1	.3555	.5698	
Density X Subject	7	2.9579	.0879	
Shade X Subject	7	2.3598	.1400	
Error	7			
Total				.70
		Level Flight		
Density	1	24.024	.0018*	.13
Shade	1	4.2614	.0779	
Subject	7	12.04	.002*	.43
Density X Shade	1	2.2269	.1793	
Density X Subject	7	4.4384	.0339*	13
Shade X Subject	7	3.8238	.0489*	.11
Error	7			
Total				.80
		Turning Flight		
Density	1	.3877	.5532	
Shade	1	16.2165	.005*	.09
Subject	7	15.9842	.0008*	.64
Density X Shade	1	.2722	.6180	
Density X Subject	7	2.0253	.1861	
Shade X Subject	7	1.7369	.2418	
Error	7			
Total				.73

*$p < .05$.

Table 5. **Mean Altitude Univariate Source Table Plus Omega Squared**

Source	df	F	p	w^2
		Total Course		
Density	1	6.6799	.0362*	.04
Shade	1	12.5286	.0095*	.07
Subject	7	14.9906	.0010*	.61
Density X Shade	1	.0915	.7711	
Density X Subject	7	1.9264	.2033	
Shade X Subject	7	2.2612	.1519	
Error	7			
Total				.72
		Level Flight		
Density	1	41.9717	.0003*	.15
Shade	1	11.2084	.0123*	.04
Subject	7	17.3627	.0006*	.42
Density X Shade	1	.4874	.5076	
Density X Subject	7	6.9007	.0104*	.15
Shade X Subject	7	5.9517	.0157*	.13
Error	7	33.5642		
Total				.72
		Turning Flight		
Density	1	.0255	.8776	
Shade	1	25.6739	.0015*	.09
Subject	7	25.9227	.0002*	.66
Density X Shade	1	1.8731	.2134	
Density X Subject	7	4.3273	.0361*	.09
Shade X Subject	7	2.3871	.1368	
Error	7			
Total				.84

*$p < .05$.

As is evident from Tables 3 through 5 (the source tables), the largest effects and the most variance can be accounted for by the differences between subjects. The subject effect is responsibile for 42% of the level flight variance and 66% of the turning flight variance (for mean values). The main subject effect size and the numerous significant interactions of density and shade conditions with subjects indicates a considerable and consistent difference between pilots and also how the factors of cue density and shade influence their individual flight performance. Typically, the subject factor accounts for a large porportion of the variance, however, in this type of experimental design, the importance of individual differences in technique, and perhaps perceptual habits, should not be overlooked.

One of the most revealing indices of the effects of these factors is their relationship to terrain avoidance. Table 6 presents a simple frequency tabulation of terrain crashes. With such small numbers, no firm and fast conclusions can be drawn about the differences between any of the cells, but it seems clear that cue density influences the pilot's ability to effect terrain avoidance. Also, the difference between the white and black cue conditions is small. Thus, even though cue shade influences the mean height and the variability in altitude control, it does not seem to be a contributor to terrain avoidance.

Table 6. **Terrain Crashes**

Cue Density	Cue Shade Black	White
1500 Feet	0	1
4500 Feet	3	4

IV. STUDY II: AIRSPEED AND OBJECT CONFIGURATION

Objectives

The original intent of providing a cue that is shaded with a white top and black bottom was to provide a clearly visible linear perspective cue. The actual function of this cue-shading technique was never experimentally tested. The results of Study I indicate the potential import of a contrast cue. Additionally, a systematic examination of the role of vertical development has not been adequately performed. Three cue conditions were used in this study: (a) black-bottomed, white-topped cues, (b) all black cues, and (c) the white tops placed coplanar with the surface (i.e., no vertical development). The specific objectives were to examine (a) terrain texture in the form of all black versus white-topped cones, (b) the effects of the presence (or absence of vertical development in terrain features, and (c) the effects of the rate of motion on the maintenance of an assigned flight altitude. The latter variable had not been studied within the same experiment; the results of the present study would provide a direct test of the airspeed (optical flow rate) factor. The difference in airspeed provides a rate of texture motion that could produce differences in depth cues, such as motion parallax. These airspeeds are also representative of the fast/slow flighter aircraft airspeeds. For similar reasons, the study also included two levels of pilot experience. Because of a small sample size in the experienced group, no direct comparison was made. Pilots with experience in actual aircraft low-level flight would be expected to perform differently than novice fighter pilots.

Method

Subjects. A total of 20 pilots participated in the study. Data from one subject was deleted due to an error in experimental test procedures. All pilots were in the process of transitioning to the F-16 aircraft, and they participated in this study after completion of a 4-hour instructional syllabus in the ASPT/F-16. Thirteen B-course pilots (mean flying time = 779 hours) and six T-course (mean flying time = 1,864 hours) served as subjects.

Equipment. Same as Study I.

Experimental Design and Procedures. The course used in study II was the same as the one used in Study I (see Figure 3). The course consisted of three legs arranged at right angles; each leg was 8 miles long and 2 miles wide. An aiming tower 450 feet high was positioned at the end of each leg. A tone was presented through the subject's headset as a cue to initiate a left or right turn as required. The turn required a 90° heading change.

Each subject received both a verbal and a written briefing prior to participation in the experiment. The subject was instructed to maintain an altitude of 200 feet AGL and to maintain his assigned airspeed for that trial (either 300 or 540 knots indicated airspeed (KIAS)). Each pilot was initialized at the desired altitude prior to the beginning of each trial. Whenever airspeed exceeded or fell below the prescribed value by more than 30 knots, an automated voice said "low, low," etc., or "high, high," etc., until the airspeed was back within the 30-knot tolerance.

The experimental design used in the study was a 3x2 (three terrain features and two airspeeds) within-subjects design. Each subject had 15 trials (about 90 minutes in the 300-KIAS condition and 50 minutes in the 540-KIAS condition). The first three trials were practice trials. On these trials, the subject was verbally informed of the altitude every few seconds by the experimenter by means of the headset communications system. On the 12 test trials, no verbal feedback was given until the trial was complete. Then, the subject was told how close the altitude was to the prescribed. Three of the six conditions were chosen at random for the three practice trials. Each of the six test conditions was repeated twice during the test trials; the sequence of conditions was randomly distributed.

All pilots were questioned immediately after participating in the experiment to determine their preference for the different terrain features (in rank order) and the different cues they used to maintian altitude.

1. *Independent Variables.* The independent variables were as follows:

a. Three types of vertical cues were used: all black inverted tetrahedrons; black-bottomed, white-topped inverted tetrahedrons; and white triangles coplanar to the surface. All tetrahedrons were 35 feet in height with about a 10-foot base. The coplanar triangles were simply the tops of the tetrahedrons. The cues were spaced irregularly throughout the course with an average inter-cue distance of 1,500 feet. This factor was a within-subject variable. The lumminance levels at the cues (as measured by a Pritchard photometer) were as follows; black .25 foot-lamberts, white top 1.15 foot-lamberts, sky 1.05 foot-lamberts, and gray ground .55 foot-lambert. These readings were taken from the front channel and vary somewhat between and within CRTs.

b. Two airspeeds were chosen: 300 and 540 KIAS. These were the same airspeeds used in separate experiments by Martin (1983). This factor was also a within-subject variable.

c. Strickly speaking, pilot experience was not an independent variable because no direct comparisons were made between the groups. Two groups of pilots were used. One group consisted of pilots with extensive previous fighter experience, and the other group consisted of recent graduates with no previous operational fighter background.

2. *Dependent Measures.* The mean altitude RMS deviation for level flight turns, as well as for the entire course, were the dependent measures used in this study. In addition, the number of terrain crashes for each of the six conditions was recorded.

V. RESULTS

The results of both studies are presented in tabular form. Results of the ANOVAs (BMDX69X) and the values of omega squared for the B-course pilots are shown in Tables 7 through 12. Tables 13 through 18 present the mean values for altitude and RMS deviation (from 200 feet) for the entire course, for level flight only, and for turns only for the same subjects. The results of the ANOVAs and the values of omega squared for the T-course pilots are shown in Tables 19 and 20, and the mean values for altitude and RMS deviation for the entire course are shown in Tables 21 and 22.

Inspection of Tables 7 and 8 showns that, in general, for the B-course (less experienced pilots), mean altitude and RMS deviation are most affected by the variables of airspeed and texture or terrain features. Tukey tests ($\underline{p} < .01$) showed that these values increased significantly with an increase in airspeed, and when triangles were used in place of either type of cone (all black or with a white-top), these factors usually accounted for the largest amount of the total variance, as shown by the values of omega squared. In addition, there was a significant subjects effect.

Table 19 shows the number of terrain crashes for each terrain feature-airspeed combination. The results are shown for both B-course and T-course (in parentheses) pilots. In general, the overwhelming number of terrain crashes for B-course pilots (16 out of 19) and T-course pilots (4 out of 5) occurred for the conditions which employed white triangles. For both groups, most crashes occurred in the right turn (20 out of 24).

The results for the T-course or more experienced pilots are shown in Tables 19 to 22. Here, the only significant effects were for airspeed and subjects, with texture being nonsignificant. Tukey tests showed these differences to be significant at a $\underline{p} < .05$.

Finally, all subjects were interviewed immediately after participating in the experiment. As indicated, they were questioned as to the cues they used in maintaining their altitude and their preferences (in rank order) of the three terrain features. All but two B-course pilots preferred the white-topped cones first, the all-black cones second, and the white triangles third. Of the two who ranked the terrain features differently, one did not discriminate between the different cones, and the other preferred the all-black cones first, followed by the white-topped cones, and then the triangles. However, the T-course pilots tended to choose the all-black cones first, the white-topped cones second, and the triangles third; however two T-course pilots reversed the order of cone preference. In all cases, the white triangles were least preferred by pilots.

Table 7. **Results of ANOVAs and Omega-Squared Values for Total Course Mean Altitude (*B-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	157.6789	.00000	.356
B (Texture)	2	15.0721	.00003	.064
S (Subjects)	12	3.3996	.00071	.066
SA	12	1.6726	NS*	
SB	24	2.3590	.00270	.074
AB	2	11.8288	.00012	.049
SAB	24	1.3167	NS*	

Note. Total variance accounted for = .609.
*$p > .01$.

Table 8. **Results of ANOVAs and Omega-Squared Values for Total Course RMS Altitude (*B-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	127.4875	.00000	.265
B (Texture)	2	38.4251	.00000	.157
S (Subjects)	12	3.4490	.00063	.062
SA	12	3.2787	.00096	.157
SB	24	3.5919	.00004	.057
AB	2	19.9981	.00001	.080
SAB	24	2.7021	.00072	.086

Note. Total variance accounted for = .837.

Table 9. **Results of ANOVAs and Omega-Squared Values for Level Flight Mean Altitude (*B-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	76.6962	.00000	.242
B (Texture)	2	8.9092	.00057	.053
S (Subjects)	12	2.5010	.00800	.061
SA	12	1.3735	NS*	
SB	24	1.7609	NS*	.062
AB	2	7.8003	.00110	.046
SAB	78	.9169	NS*	

Note. Total variance accounted for = .464.
*$p > .01$.

Table 10. **Results of ANOVAs and Omega-Squared Values for Level Flight RMS Deviation (*B-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	53.3613	.00000	.140
B (Texture)	2	28.1642	.00000	.145
S (Subjects)	12	2.8286	.00320	.058
SA	12	2.2340	NS*	.040
SB	24	2.5209	.00140	.097
AB	2	11.2513	.00016	.055
SAB	24	1.7761	.00200	.050

Note. Total variance accounted for = .585.
*$p > .01$.

Table 11. **Results of ANOVAs and Omega-Squared Values for Mean Altitude in Turns (*B-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	150.2852	.00000	.336
B (Texture)	2	5.6762	.00530	.021
S (Subjects)	12	3.998	.00018	.081
SA	12	2.0398	NS*	.028
SB	24	2.0505	.00950	.057
AB	2	15.1466	.00003	.064
SAB	24	2.1350	.00670	.061

Note. Total variance accounted for = .648.
*$p > .01$.

Table 12. **Results of ANOVAs and Omega-Squared Values for RMS Deviation in Turns (*B-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	132.6463	.00000	.275
B (Texture)	2	22.7085	.00000	.090
S (Subjects)	12	4.0118	.00018	.075
SA	12	2.6707	.00490	.041
SB	24	2.4008	.00230	.069
AB	2	14.7426	.00003	.057
SAB	24	2.4919	.00160	.074

Note. Total variance accounted for = .678.

Table 13. **Means for Total Course Altitude (*B-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	540 KIAS
White Triangles	184.67422	325.42537
All-Black Cones	181.56306	251.35844
White-Topped Cones	178.63768	241.35844

Table 14. **Means for Total Course RMS Deviation (*B-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	540 KIAS
White Triangles	69.71000	179.43349
All-Black Cones	54.67442	91.64188
White-Topped Cones	56.71627	93.70199

Table 15. **Means for Level Course Altitude (*B-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	540 KIAS
White Triangles	188.36998	297.30613
All-Black Cones	180.61845	238.01498
White-Topped Cones	188.81345	223.54767

Table 16. **Means for Level Course RMS Deviation (*B-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	540 KIAS
White Triangles	67.52399	135.45772
All-Black Cones	52.86430	72.22788
White-Topped Cones	53.79326	72.73411

Table 17. **Mean Altitude in Turns (*B-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	540 KIAS
White Triangles	171.28680	401.36383
All-Black Cones	188.53729	300.12997
White-Topped Cones	204.14268	287.40229

Table 18. **Mean RMS Deviation in Turns (*B-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	540 KIAS
White Triangles	80.73184	257.50613
All-Black Cones	63.57426	139.19199
White-Topped Cones	72.13561	138.29910

Table 19. **Results of ANOVAs and Omega-Squared Values for Total Course Mean Altitude (*T-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	15.8053	.00056	.142
B (Texture)	2	2.7343	NS*	
S (Subjects)	5	3.4305	.01200	.117
SA	5	.8644	NS*	
SB	10	.8319	NS*	
AB	2	2.5672	NS*	
SAB	10	1.0821	NS*	

Note. Total variance accounted for = .259.
*$p > .05$.

Table 20. **Results of ANOVAs and Omega-Squared Values for Total Course RMS Deviation (*T-Course Pilots*)**

Source	df	F	p	w^2
A (Airspeed)	1	15.0883	.00068	.146
B (Texture)	2	1.4724	NS*	
S (Subjects)	5	3.3790	.01300	.124
SA	5	.9841	NS*	
SB	10	.4533	NS*	
AB	2	2.0138	NS*	
SAB	10	1.0802	NS*	

Note. Total variance accounted for = .270.
*$p > .05$.

Table 21. **Means for Total Course Altitude (*T-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	Airspeed 540 KIAS
White Triangles	227.62916	244.31249
All-Black Cones	212.40166	304.33999
White-Topped Cones	193.13500	246.25083

Table 22. **Means for Total Course RMS Deviation (*T-Course Pilots*)**

Cue Type	Airspeed 300 KIAS	Airspeed 540 KIAS
White Triangles	84.43766	108.84358
All-Black Cones	56.66975	140.53158
White-Topped Cones	55.31591	094.11016

With regard to the kinds of cues the pilots reported they used, several interesting and often similar comments were made by subjects from both groups (B-course and T-course pilots). The main comments involved the following: (a) the use of HUD as a visual reference relative to the aiming towers or the horizon, (b) the use of peripheral vision and the flow of streaming of cues, (c) the necessity of having vertically developed terrain features, (d) the relative height of the terrain features and the aiming towers, (e) the rate of movement of the terrain features, (f) the size of the white triangles, and (g) the use of the vertical velocity indicator (VVI) in the cockpit to provide an indirect indication of altitude. Few differences were observed between the comments of B-course and T-course pilots.

In general, the results obtained with both groups of subjects (B-course and T-course pilots) in the present study show that airspeed has the greatest effect on the dependent variables of mean altitude and RMS deviation. In other words, an increase in airspeed from 300 to 540 KIAS produced a significant increase in mean altitude and RMS deviation. However, less experienced pilots (B-course) also show significantly increased altitude and RMS deviation measures at the higher airspeed when there is a lack of vertical development in the terrain features (white triangles versue cones). This effect was not found with the more experienced pilots (T-course), which may suggest they are better able to utilize other cues in their visual environment (e.g., the VVI, the HUD frame, the windscreen frame, and the combining glass of the HUD), in the absence of vertically developed terrain features. No significant effects were found when texture in the form of contrast was manipulated (all-black versue white-topped cones) for either group. Thus, vertical development appears to be the most important terrain feature. This finding is emphasized when the data for terrain crashes are examined (see Table 23). As previously noted, most of the crashes occurred when using the white triangles for both groups. This indicates that vertical development is also important to the more experienced, as well as the less experienced, pilots.

Table 23. **Terrain Crashes as a Function of Experimental Conditions**

Cue Type	Airspeed 300 KIAS	Airspeed 540 KIAS
White Triangles	9 (2)	7 (2)
All-Black Cones		1
White-Topped Cones	1 (1)	1

Note. Values in parentheses refer to T-course pilots; all others refer to B-course pilots.

A significant subject effect with both B-course and T-course pilots may well be due to the differences in their flying experience. Pilots in both courses tended to vary both in the number of hours (SD = 684 for B-course and SD = 767 for T-course pilots) and the type of aircraft flown.

VI. DISCUSSION

Two studies were conducted investigating the role of vertical cue development as an aid to low-level flight in a flight simulator equipped with a computer-generated imagery system. The ASPT in its F-16 configuration was used in this research. It is equipped with a monochromatic seven-channel pancake window visual display which covers a field of view of $\pm 150°$ H by $+110°$ V. Pilots transitioning into the F-16 aircraft served as subjects in the experiments. The pilots in Study I and one of the groups in Study II were B-course pilots; they had no previous experience in fighter aircraft experience. Their participation in the present effort followed completion of a 4-hour course of instruction in the ASPT on transition and conventional weapons delivery tasks.

The experimental task used in the effort was a course consisting of three straight path segments separated by two right angle turns; the first turn was to the left and the second turn to the right. At 540 knots, approximately 6g turn was required to remain on the course. Each leg was 8 nautical miles long and 2 nautical miles wide. Scattered throughout the course were vertical cues whose type and density were varied on each trial. The pilot's task was to fly through the course at a prescribed altitude and airspeed using the cues as the primary reference for accomplishing the task. There were no cockpit or HUD indications of altitude, velocity vector, vertical velocity, pitch, bank or airspeed. The performance measurement system on the ASPT was programmed to monitor the altitude, airspeed, bank, and g-forces throughout each trial.

In Study I, cue density and cue shade were manipulated as the independent variables. The cues were tetrahedrons (pyramids) that were 75 feet high with a 32-foot base. The cue shades were either solid black or solid white. Two density levels were used. In the most dense condition, the cues were spaced irregularly throughout the course at an average inter-cue distance of 1500 feet. In the least dense condition, the average spacing distance was 4500 feet. The pilots were asked to fly through the course at 100 feet AGL and to maintain 540-knots airspeed. Thus, for any given trial, the pilot might see white pyramids spaced at an average of 4500 feet, and the next trial the pilot might see black pyramids spaced at an averge of 1500 feet. All pilots were exposed to each of the four cue conditions twice; the average of the two trials was used as the data for subsequent analysis. The results of the study indicated that both the cue density and the cue shade significantly influenced the pilot's ability to maintain altitude. The more dense condition and the white cue condition were superior to the less dense and black cue condition, respectively. Even though the white shade cue was a more effective cue, the pilots unanimously preferred the black cues. The cue density was not as much a factor in the turns as it was for level flight, but the white shade maintained an influence during the turns. The cue density factor was the primary variable aiding terrain avoidance. The shade of the cue did not seem to affect terrain avoidance.

In Study II, three types of terrain cue conditions were investigated as well as two airspeeds. Inverted tetrahedrons (cones), 35 feet high with a 10-foot base, were shaded either all black or shaded with a black bottom and a white top. As a third condition, the white triangularly shaped top was placed directly on the ground surface at the same spacing as the cone shaped cues. The purpose of the white top was to provide a linear perspective cue to altitude change. By comparing the white tops placed directly on the ground (i.e., no vertical development) with the cone conditions, the importance of the vertical development, per se, can be assessed. Two airspeeds, 300 and 540 knots, were used. The task altitude in this study was 200 feet AGL. A 1500-foot average inter-cue spacing was used in all trials. Two groups of pilots were used in this experiment. One group was comprised of experienced fighter pilots; and the other group was made up of pilots with less overall flight experience and no previous fighter assignments. All pilots were exposed to all six treatment conditions (three terrain conditions combined with two airspeeds). The results of this study indicated that altitude control was better at 300 knots than at 540 knots for both experienced and inexperienced pilots. For the experienced pilots, there was no significant difference in altitude control between the three cue conditions, but for the inexperienced pilots, the two vertically developed cues were better than the condition with the white triangles on the ground. There was no difference between the cues with the white tops and those which were solid black. For both groups, the white top only condition (i.e., no vertical development) was associated with more terrain crashes than were the two vertical cue conditions.

The finding from Study I that cue density is a signficant factor affecting altitude control further confirms earlier results (Martin, 1983) relating cue density to altitude control. Martin reported that object density was a significant factor affecting altitude control at 540 knots but not at 300 knots. Engle (1980) also failed to find a significant effect of object density when an experimental task was flown at 300 knots. Using a different task and an A-10 flight simulation, Engle varied object density between 500- and 1500-foot spacings at 250-foot increments. Study II of the present research demonstrated that altitude control at 300 knots is significantly better than at 540 knots. Thus, it appears that object density is a significant factor under conditions of difficult flight but not under easier control conditions (at least at object density levels between 500 and 4500 feet). These findings have some obvious implications for data base modeling and for theoretical notions on space and depth perception. The role of object density is clearly not a simple linear function of information rate or absolute numbers.

Perhaps the most surprising finding of these experiments is that the white cues were significantly better than the black cues in aiding altitude control, and that the magnitude of the effect is approximately the same as for cue density. (It is suprising because the pilots unanimously preferred the black cues.) The difference in effectiveness is most easily attributed to the relative contrast differences. The black cues were measured at .22 foot-lamberts compared with 1.2 foot-lamberts for the white cues, both set against a gray background with a luminance reading of .60 foot-lamberts. The percent contrast (as defined by Blackwell, 1946) are 100% and 63% for the white and black cues, respectively. For static viewing conditions, it is well established that visual performance (in terms of traditional acuity measures) depends greatly on luminance values and target-to-background contrast. (See Cobb and Moss, 1928; and Blackwell, 1946 for relevant psychophysical data.) Given the 6-arc-minute resolution of the ASPT visual system and the relatively low luminance levels (e.g., compared to 1000 foot-lamberts for a clear day), it is not surprising that the white cues and the greater associated contrast would provide a significantly more visible, and presumably more useful, cue. Contrast sensitivity, for example, has been previously shown to relate to simulator visual detection performance under passive dynamic viewing conditions (Ginsburg, Evans, Sekuler, & Harp 1982). Supra-threshold sensitivity to other visual dimensions, specifically changing size, lateral motion, and flow pattern expansion has been empirically shown to correlate with dynamic pilot control performance (Kruk, Regan, Beverley, & Longridge, 1981; Kruk, Regan, Beverley, & Longridge, in press; Kruk & Regan, in press). It is possible that the white cones were a more effective stimulus for visual mechanisms selectively tuned to the latter dimensions, but the conditions of this experiment did not permit an experimental test of this hypothesis.

The experimental flight task consisted of three straight-ahead segments connected by two right-angle turns. The data from the level segments were separated from the data collected during the turns because it is clear to even the casual observer that they are two different tasks. The results of the data analyses suggest that the visual cues are used differently during these two phases of flight. It can be seen from the analyses of the average altitude (Table 5) that while cue density and cue shade were significant factors during level flight, cue density accounted for more than three times the variance than did cue shade, 15% and 4%, respectively. However, during maneuvering flight, cue density is not a significant factor whereas cue shade continues to be an effective cue. When considering the efficiency of flight control as well as the raw altitude (i.e., the RMS data), the relative differentiation of cue function is more striking because cue density but not cue shade is significant during level flight and cue shade but not cue density is significant during maneuvering flight. The terrain crash data also support the position that cue density and cue shade function differently. From Study I, it can be seen that the frequency of terrain crashes was higher when there were less cues, suggesting that density is important for terrain avoidance whereas there was not much difference between the white cues and the black ones.

Consideration of the visual strategies that the pilots reported using supports a cue differentiation position. For level flight, pilots reported their main cues for altitude were either those directly in front or those close by either side. Since the cues were 75 feet high, the pilots could gauge the desired 100 feet AGL by being just "slightly" above the cue tops. Many pilots reported intentionally flying a course which placed the cues close to the aircraft for this purpose to "calibrate their eyeballs." As the cues approached and passed by, the pilots would focus on them. However, when there were none in the immediate vicinity, they reported concentrating on placing the aiming tower (located at the end of each leg), in a specific intersection point with the horizon to maintain the desired altitude. Thus, for much of level flight, pilots placed altitude-gauging cues in their foveal visual field. It is logical, then, that the more cues available for gauging their altitude, the more accurate and efficient their flight path would be.

The strategies reported for use during the turns varied somewhat, but all had some common elements. Most pilots reported focusing on the horizon and not coming back to the ground visual scene until they needed to find the aiming tower to use as the roll-out cue. The appropriate bank angle was established first, and some aircraft reference (usually the frame of the HUD) was then used to establish an altitude change reference. Other than the use of the aiming tower for a reference for judging the extent of the turn, the pilots reported being unaware of the ground cues during the turns. (This is not surprising since pilots are instructed not to look directly at the ground when maneuvering due to the tendency to fly where they are looking.) Given this visual scan pattern during turns, the vertical object cues would most often be in the lower front and lateral visual fields. Thus, the influence of the white cues (presumably due to a contrast effect) was probably affected by stimulation of the peripheral visual field. Although it is unwise to place too much credence on pilot reports regarding cue function, it at least provides suggestive leads for future research. It would obviously be desirable to have an actual focal point, eye-recording system available for research relating cue function to locus of visual field presentation.

The large amount of variance accounted for by the subject factor and various subject interactions are indicative of the sensitivity of this task to individual differences. If these differences could be related to some other meaningful factor such as visual contrast sensitivity or control strategy, further understanding of the operating perceptual mechanisms could be achieved. Regan (1982), for example, reports that there are at least 4:1 variations in contrast sensitivity at intermediate spatial frequencies for control subjects with similar Snellen acuities, and that there are 80:1 intersubject differences in the relative effectiveness of changing size and stereo-motion inputs as stimuli for motion in depth.

The results of the second study are most informative with respect to the need for vertical development. Buckland (1981) had reported that checkered ground patterns were more influential than were vertical objects. However, his experimental paradigm did not present a good test of that question. As noted earlier, checkered patterns of the type used in the Buckland study are extemerly edge costly; tetrahedrons spaced at 1500-foot intervals are considerably more edge efficient. Placing a triangle on the ground requires only three edges per cue compared to six for a solid three-sided object, so the if flat cues were as effective as vertical cues, additional edge savings could have been achieved. With respect to the linear perspective cue, the flat cue would provide almost the same information as the tops of the inverted tetrahedrons. The results of this study indicate that the vertical development clearly aids terrain avoidance and helps the inexperienced pilot control altitude. (The experienced pilots also did better with vertically developed cues, but the effect was not statistically significant.) Thus, the investment in the extra edges (to obtain verticality) is well worth the cost.

The original notion behind the design of an inverted tetrahedron (as opposed to an upright cue such as used in Study I) was to provide an additional perspective cue (i.e., the triangular top) that could aid low altitude flight. The intent of shading the top white (which does not consume any additional edges compared to a uni-shaded object) was to make the top more visible (by increasing contrast). Some of the pilots indicated that the linear perspective cue was useful to aid judgment in rate of descent and hence, to aid terrain avoidance. However, the results of this study indicate that, as a general rule, the white shade does not significantly enhance altitude control or terrain avoidance. The fact that the white cues in Study I were superior to the black cues would lead one to predict that the white-topped cues should also be associated with better altitude control. Difference in cue size may account for this seeming inconsistency; only 35 feet high, with the white area only a 10-foot equilateral triangle. The difference in size is compounded by the difference in task altitude, 100 feet in Study I (i.e., 25 feet above the cue top) and 200 feet in Study II (i.e., 165 feet above the cue top).

VII. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this research and the previous work in this area, the following conclusions and recommendations are offered:

1. For high speeds (e.g., 540 knots) and low altitudes (e.g., less than 300 feet AGL), it is recommended that vertically developed objects be placed over the terrain at inter-cue distances of approximately 1500 feet. This spacing requirement requires 96 edges per square mile (assuming a tetrahedron-shaped object is used).

2. The spacing requirement for slower airspeeds (e.g., 300) knots has not been determined but might be less than for the higher speeds.

3. Cue constrast should be maximized, particularly when using relatively low luminance displays.

4. Vertical development (at the 1500-foot spacing) is not a sufficient cue for terrain avoidance during difficult aircraft maneuvering.

REFERENCES

Blackwell, H.R. Contrast thresholds of the Human Eye. *Journal of the Optical Society of America*, 1946, **36**, 624.

Buckland, G.H., Edwards, B.J., & Stephens, S. Flight Simulator Visual Development and Instructional Features for Terrain Flight Simulation. In *Proceedings of the 1981 Image Generation/Display Conference II*, June 1981, 351–362. AFHRL-TR-81-48, AD-A110 226. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Buckland, G.H., Monroe, E.G., & Mehrer, K.I. *Flight simulator runway visual textural cues for landing*. AFHRL-TR-79-81, AD-A089 434. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory, August 1980.

Cobb, P.W., & Moss, F.K. The four variables in the visual threshold. *Franklin Institute Journal*, 1928, **205**, 831.

Engle, R.L. *Use of low altitude visual cues for flight simulation*. Unpublished Masters Thesis, Arizona State University, Tempe, Arizona, December 1980.

Fuller, J.H., Waag, W.L., & Martin, E. L. *Advanced simulator for pilot training: Design of automated performance measurement system*. AFHRL-TR-79-57, AD-A088 855. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory, August 1980.

Ginsburg, A.P., Evans, D.W., Sekuler, R., & Harp, S.A. Contrast sensitivity predicts pilots performance in aircraft simulators. *American Journal of Optics and Physiological Optics*, 1982, **59**, 105–109.

Graham, C.H. Visual space perception. In C.H. Graham, (Ed.), *Vision and Visual Perception*, New York: Wiley and Sons, Inc., 1965.

Gum, D.R., Albery, W.R., & Basinger, J.D. *Advanced simulation in undergraduate pilot training: An overview*. AFHRL-TR-75-59 (I), AD-A030 224. Wright-Patterson AFB, OH: Advanced Systems Division, Air Force Human Resources Laboratory, December 1975.

Harker, G.S., & Jones, P.D. *Depth perception in visual simulation*. AFHRL-TR-80-19, AD-A087 828. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory, August 1980.

Kellogg, R.S., Prather, D.C., & Castore, C.H. Simulated A-10 combat environment, in *Proceedings of the 1981 Image Generation/Display Conference II*, June 1981, 36–44. AFHRL-TR-81-48, AD-A110 226. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Kraft, C.L. Measurement of height and distance information provided pilots by the extra-cockpit visual scene. In *Visual Factors in Transportation Systems, Proceedings of Spring Meeting, 1969, NAS–NRC Committee on Vision*. Washington, D.C.: National Academy of Sciences, 1969.

Kruk, R., & Regan, D. Visual test result compared with flying performance in telemetry-tracked aircraft. *Aviation space and environmental medicine*, in press.

Kruk, R., Regan, D., Beverley, K.I., & Longridge, T. Correlations between visual test results and flying performance on the advanced simulator for pilot training (ASPT). *Aviation Space and Environmental Medicine*, 1981, **52**, 455–460.

Kruk, R., Regan, D., Beverley, K.I., & Longridge, T. Flying performance on the advanced simulator for pilot training and laboratory tests of vision. *Human Factors*, in press.

Martin, E.L. *The role of object density in simulated low level flight*. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory, in preparation.

Regan, D. Visual information channeling in normal and disordered vision. *Psychological Review*, 1982, **89**, 407–444.

Stenger, A.J., Zimmerlin, T.A., Thomas, J.P., & Braunstein, M. *Advanced computer image generation techniques exploiting perceptual characteristics.* AFHRL-TR-80-61, AD-A103 365. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory, August 1981.